



## Disorder and *c*-axis quasiparticle dynamics in underdoped Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8</sub>

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# Disorder and $c$ -axis quasiparticle dynamics in underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$

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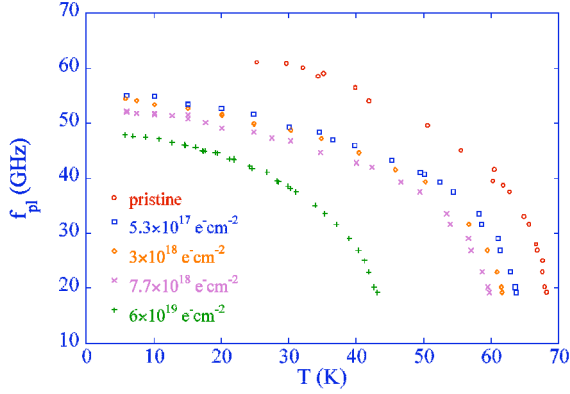
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**Abstract.** We present measurements of the Josephson plasma frequency and the in-plane penetration depth of underdoped single crystalline  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  with varying degrees of disorder introduced by irradiation with 2.3 MeV electrons. Increasing disorder drives  $T_c$  down, in agreement with in all model descriptions of high  $T_c$  superconductivity. However, the manner in which the JPR frequency, the square of which represents the zero-frequency spectral weight of the  $c$ -axis conductivity in the superconducting state, is driven down by disorder depends more strongly on the model description. We show that only the model of impurity assisted quasiparticle hopping in a  $d$ -wave superconductor, together with strongly scattering point defects in the superconducting layers, can explain the disorder dependence of the  $c$ -axis plasma frequency, the in-plane penetration depth, and  $T_c$  consistently. From the data, we extract the energy scale governing nodal quasiparticle excitations,  $\Delta_0 \sim 2.5k_B T_c$ .

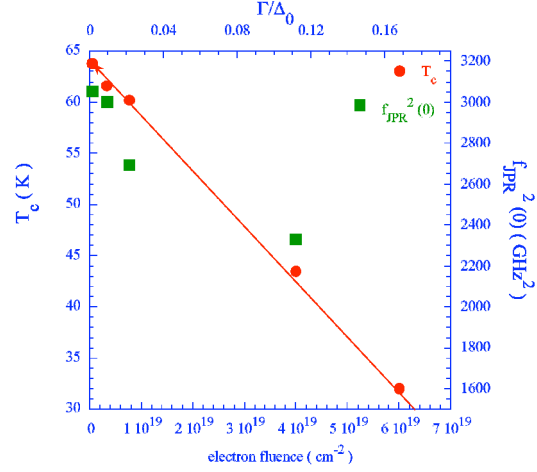
## 1. Introduction

The nature of the normal state in underdoped cuprates figures prominently among controversies concerning high temperature superconductivity. First, the temperature regime above the critical temperature  $T_c$  is characterized by the existence of the so-called “pseudo-gap”, the origin of which is believed to be either due to preformed Cooper pairs [1,2], with Bose condensation at  $T_c$ , or, alternatively, to the onset of an electronically ordered state competing with superconductivity [3]. The “bosonic” preformed-pair scenario was invoked to explain the violation of the Glover-Tinkham-Ferrell optical sum-rule by the  $c$ -axis conductivity[2], with the corollary that the zero-frequency peak in the  $c$ -axis spectral weight should be depressed due to in-plane quantum fluctuations of the phase  $\phi_{\parallel}$  of the superconducting order parameter.

Second, underdoped cuprates are, even more than their optimally doped and overdoped counterparts, prone to significant amounts of crystalline disorder [4-6]. Given the  $d$ -wave symmetry of the superconducting gap function, disorder is responsible for the enhancement of the quasiparticle density of states near the  $(\pi, \pi)$  direction of the gap nodes [6,7], but also for



**Figure 1.** JPR frequency vs. temperature for underdoped  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  single crystals irradiated with different fluences of high energy electrons.



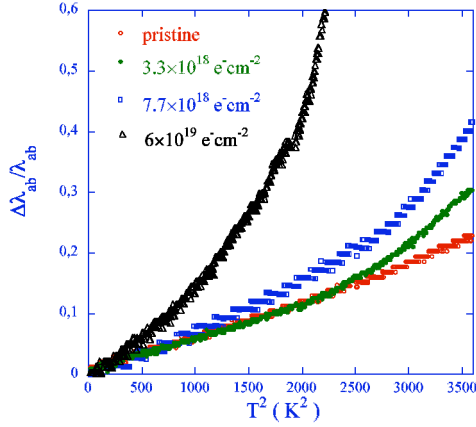
**Figure 2.** Critical temperature  $T_c$ , and square  $f_{pl}^2(0)$  of the low temperature extrapolated JPR frequency, as function of the electron fluence.

quasiparticle scattering and, likely, an ensuing depression of  $T_c$ .

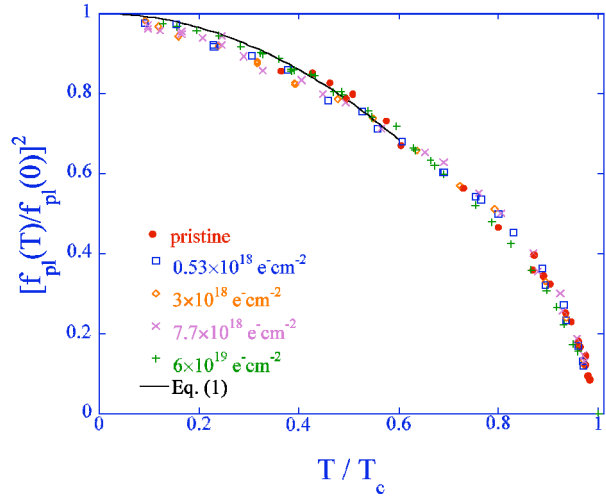
In this contribution, we study the decrease with disorder of the Josephson Plasma Resonance (JPR) frequency  $f_{pl}$ , which is a bulk probe of superconductivity, in single-crystalline underdoped  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ . Different levels of homogeneous disorder are artificially introduced by high energy electron irradiation. The results are cross-correlated with the behaviour of the penetration depth for supercurrents in the  $\text{CuO}_2$  planes,  $\lambda_{ab}$ . We find that the evolution of  $T_c$ ,  $f_{pl}$ , and  $\lambda_{ab}(T)$  with the electronic scattering rate  $\Gamma$  is consistent with the  $d$ -wave Bardeen-Cooper-Schrieffer (BCS) model for superconductivity, in which  $f_{pl}$  is reduced with increasing temperature and disorder due to the impurity assisted hopping (IAH) of nodal quasiparticles [8-11]. results. Whereas the similar temperature dependence of  $\lambda_{ab}^{-2}$  and  $f_{pl}^2$  is in good agreement with a model for strong quantum fluctuations [2,12,13], the disorder dependence is not.

## 2. Experimental details

Underdoped  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  single crystals with 0.10 holes per Cu and  $T_c = 65$  K were grown using the travelling-solvent floating zone method under 25 mBar  $\text{O}_2$  partial pressure [14]. Different crystals cleaved from the same piece were irradiated to varying fluences of 2.3 MeV electrons using the van de Graaff accelerator of the Laboratoire des Solides Irradiés. The crystals were immersed in liquid hydrogen during the irradiation. The irradiation produces homogeneously distributed point defects (Frenkel pairs), both in the  $\text{CuO}_2$  layers and in the  $\text{BiO}$  insulating blocking layers. The effect of the former is expected to be similar to Zn-doping [15]. The JPR frequency was measured by placing the sample on the centre of the top surface of a high conductivity copper resonant cavity, and measuring the cavity resonance as function of  $T$ ; at the temperature at which the absorption is maximum,  $f_{pl}$  is equal to the resonant mode frequency. This procedure was repeated for different harmonic transverse modes  $TM_{01n}$ . Additional swept-frequency measurements were made at the University of Tokyo by exploiting the  $TE_{01}$  travelling wave mode of a waveguide together with bolometric detection of an increase in the surface resistance [16]. Finally, the temperature variation of  $\lambda_{ab}$  of the irradiated crystals was measured using a Pb resonant cavity at Kyoto University.



**Figure 3.** Temperature variation of the *ab*-plane penetration depth of underdoped  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  crystals for different electron irradiation fluences.



**Figure 4.**  $f_{pl}^2(T)/f_{pl}^2(0)$  vs. reduced temperature  $T/T_c$ , for different electron irradiation fluences.

### 3. Results

All crystals showed well-defined peaks in the *c*-axis surface resistance, permitting the identification of the JPR. The  $f_{pl}(T)$  curves, depicted in Fig. 1, show that  $f_{pl}$  vanishes at the bulk  $T_c$  of the underdoped crystals, and allow for the determination of the low-temperature extrapolated value  $f_{pl}(0)$ . Fig. 2 shows that both  $T_c$  and  $f_{pl}^2(0)$  decrease linearly as function of electron fluence. The linear decrease of  $T_c$  is expected from the pair-breaking effect of the irradiation-induced defects in the  $\text{CuO}_2$  planes [17]. This is corroborated by the  $T^2$ -dependence of the *ab*-plane penetration depth (Fig. 3), which points to an important role of quasi-particle scattering in the unitary limit in all crystals [18]. We can then directly compare the evolution of  $T_c$  with fluence to the results [20] and obtain an estimate of the normal state scattering rate  $\Gamma$  normalized to the energy scale  $\Delta_0$  governing quasiparticle excitations (see Fig. 2).

In spite of the widely varying disorder levels,  $f_{pl}^2$ , which is proportional to the spectral weight of the zero-frequency peak in the *c*-axis conductivity in the superconducting state (or *c*-axis superfluid density  $\rho_s^c$ ), has the same  $T$ -dependence for all crystals. Fig. 4 shows that all data overlap when plotted as  $f_{pl}^2(T)/f_{pl}^2(0)$  vs  $T/T_c$ , and that  $f_{pl}^2(T)/f_{pl}^2(0) \propto 1 - a(T/T_c)^2$ .

### 4. Discussion

The observed temperature and disorder dependence of  $f_{pl}$ ,  $T_c$ , and  $\lambda_{ab}$ , imposes important constraints on a model interpretation. Notably, the proportionality of  $f_{pl}^2(0)$  with  $T_c$  excludes the scenario where the *c*-axis superfluid density is reduced through direct quasiparticle tunnelling [8]. Good agreement is obtained, however, by considering incoherent tunnelling of nodal quasiparticles mediated by interlayer impurity states. In this case, one expects [9,10]

$$\rho_s^c = 2\pi V_1 \Delta_0 N^2(E_F) \left[ 1 - 8 \ln 2 \left( \frac{T}{\Delta_0} \right)^2 \right], \quad (1)$$

where  $V_1$  is the anisotropic part of the interlayer impurity potential, and  $N(E_F)$  is the density of states at the Fermi level. Eq. (1) consistently describes the temperature and the disorder dependence of  $f_{pl}$ , as well as the “scaling” observed in Fig. 4, if we assume that  $\Delta_0 = 2.5k_B T_c$  regardless of the disorder level. This number is in very good agreement with that obtained from Scanning Tunnelling Spectroscopy [19,20] and  $B_{2g}$  Raman spectroscopy measurements [21], which also probe the nodal quasiparticle excitations. The data are also in agreement with the toy model of Ref. [11], which predicts  $\rho_s^c \sim 1 - \frac{3}{14}(\Gamma/\Delta_0) - \dots$ . Note that in Fig.

4, the behaviour of the pristine crystal is indistinguishable from that of the irradiated ones. Hence, disorder plays an important role even without irradiation, and  $T_c$  of underdoped high temperature superconductors may be considerably suppressed with respect to a hypothetically “clean” material.

In a scenario where quantum fluctuations of the in-plane superconducting phase are predominant, the  $c$ -axis superfluid density is reduced by a “Debye-Waller” factor,  $f_{pl}^2 \sim f_{pl}^2(0) \left(1 - \frac{1}{2}\langle\phi_{\perp}^2\rangle\right) \sim 1 - \frac{1}{2}C\langle\phi_{\parallel}^2\rangle$ , while its  $T$ -dependence is only weakly affected ( $\phi_{\perp}$  is the phase difference between adjacent layers and  $C$  is a constant of order 1). Developping this expression using the results [9,10], one has

$$f_{pl}^2 \propto 1 - \frac{C}{2} \left( \frac{e^2}{\epsilon \xi_0} \frac{1}{\rho_s^{ab}s} \right)^{1/2} \frac{\lambda_{ab}(T)}{\lambda_{ab}(0)} \quad (2)$$

(where  $\rho_s^{ab}(0)$  is the low temperature in-plane superfluid density,  $\xi_0$  the coherence length,  $s$  the  $\text{CuO}_2$  layer spacing,  $e$  the electronic charge, and  $\epsilon$  the relative dielectric constant). Eq. (2) well describes the similar temperature dependence of  $f_{pl}^2$  and  $\lambda_{ab}^{-2}$ . However, it cannot reconcile the superposition of the curves in Fig. 4 with the linear decrease of  $f_{pl}^2(0)$  vs.  $\Gamma$  - the two lead to different dependences of  $\lambda_{ab}$  on  $\Gamma$ .

Summarizing, we find that the temperature- and disorder dependence of the  $c$ -axis JPR in underdoped  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  is in good agreement with a  $d$ -wave BCS model for impurity assisted nodal quasiparticle tunnelling between  $\text{CuO}_2$  layers. We extract an energy scale governing nodal quasiparticle excitations that coincides with that found in other experiments [19-21].

## References

- [1] Emery V J and Kivelson S A 1995 *Nature* **374**, 434
- [2] Ioffe L B and Millis A J 1999 *Science* **285**, 1241; 2000 *Phys. Rev. B* **61**, 9077
- [3] See Sachdev 2003 *Rev. Mod. Phys.* **75**, 913 for a review.
- [4] Cren T, Roditchev D, Sacks W, Klein J, Moussy J-B, Deville-Cavellin C, and Laguës M 2000 *Phys. Rev. Lett.* **84**, 147
- [5] Pan S H, O’Neal J P, Badzey R L, Chamon C, Ding H, Engelbrecht J R, Wang Z, Eisaki H, Uchida S, Gupta A K, Ng K-W, Hudson E W, Lang K M, and Davis J C 2001 *Nature* **413**, 282
- [6] Lang K M, Madhavan V, Hoffman J E, Hudson E W, Eisaki H, Uchida S, Davis J C 2002 *Nature* **415**, 412
- [7] See *e.g.* Hussey N E 2002 *Adv. Phys.* **51**, 1685 for a review.
- [8] Radtke R J, Kostur V N, and Levin K 1996 *Phys. Rev. B* **53**, R522
- [9] Xiang T and Wheatley J M 1996 *Phys. Rev. Lett.* **77**, 4632
- [10] Xiang T, Panagopoulos C, and Cooper J R 1998 *Int. J. Modern Physics B* **12**, 1007; cond-mat/9807404.
- [11] Kim W and Carbotte J P 2001 *Phys. Rev. B* **63**, 054526
- [12] Paramekanti A, Randeria M, Ramakrishnan T V, and Mandal S S 2000 *Phys. Rev. B* **62**, 6786
- [13] Paramekanti A 2002 *Phys. Rev. B* **65**, 104521
- [14] Li M, van der Beek C J, Konczykowski M, Menovsky A, Kes P.H. 2002 *Phys. Rev. B* **66**, 024502
- [15] Rullier-Albenque F, Viellefond P A, Alloul H, Tyler A W, Lejay P, Marucco J F 2000 *Europhys. Lett.* **50**, 81
- [16] Gaifullin M B, Matsuda Y, Chikumoto N, Shimoyama J, Kishio K, Yoshizaki R, *Phys. Rev. Lett.* **83**, 3928 (1999).
- [17] Sun Y and Maki K 1995 *Phys. Rev. B* **51**, 6059
- [18] Preosti G, Kim H, Muzikar P 1994 *Phys. Rev. B* **50**, 1259
- [19] Deutscher G 1999 *Nature* **397**, 410
- [20] Sacks W, Cren T, Roditchev D, Douçot B 2006 *Phys. Rev. B* **74**, 174517
- [21] Le Tacon M, Sacuto A, Georges A, Kotliar G, Gallais Y, Colson D, and Forget A 2006 *Nat. Phys.* **2**, 537